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Large Pile Group Design Optimization with Lateral Resistance of Pile Cap

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ABSTRACT

Lateral earth resistance of pile cap is usually ignored in the design practice in the United States. This part of lateral resistance could be significant for a large pile group design, particularly when the lateral load controls the design. A method is presented to calculate the lateral resistance of the pile cap based on FEMA 356 and compared with an approach from the Chinese Design Code. With the consideration of lateral resistance of the pile cap, an optimum spacing is found for a large strip-shape pile group to provide maximum lateral resistance. This design approach is applied to a case study – a natural gas-fueled turbine power plant built near Nanjing City, China.

INTRODUCTION

Pile foundation is usually designed as pile group to support superstructure. The group of piles is connected together by concrete pile caps. For industry facilities and high rise residential buildings, the pile caps are often massive and deeply buried and would be expected to provide significant resistance to lateral loads. However, this part lateral resistance is usually ignored in the practical piling design in the United States for many reasons including, the lateral displacement of the pile cap is not large enough to mobilize passive resistance and the possibility that soil can settle away from the cap and that piles will sustain the full load (UFC, 2004).

The lateral resistance of the pile cap includes two parts – the lateral earth resistance of the pile cap and the friction resistance between the bottom of the pile cap and the soil. Several field load tests have been performed in the area of pile cap resistance to lateral loads. Beatty (1970) performed the load tests on two six-pile groups and determined that approximately 50 percent of the applied lateral load was resisted by passive pressure on the pile cap. The pile caps of the pile groups were embedded into the ground and the lateral resistance of the front pile cap was considered. Kim and Singh (1974) performed the load tests on three six-pile groups with the pile cap constructed on the ground surface, and thus the results do not include any passive resistance at the front of the cap or frictional resistance of soil along the sides of the cap. They found that removal of soil beneath the pile caps significantly increased the measured deflections, rotations, and bending moments of single pile. Rollins et al. (1997) performed statnamic lateral testing on a group of nine piles and determined the lateral load resistance of the pile cap was greater than the lateral resistance provided by the piles themselves. Only the passive resistance at the front of the cap was considered in their tests. Zafir and Vanderpool (1998) performed load tests on a four drilled shaft group with three-meter-thick cap embedded beneath the ground surface, and determined that the lateral load resistance of the cap was approximately equal to the lateral resistance provided by the drilled shafts. These studies indicate that the lateral resistance of pile caps can be quite significant, especially when the pile cap is embedded beneath the ground surface.

Lateral capacity becomes to control design of large pile group for many facilities built in the high seismic areas. Sometime, the pile group could not be design without considering the lateral resistance of the pile cap. There is a need for evaluating the magnitude of pile cap resistance and including this resistance in the design of pile groups to resist lateral loads. Two different methods for including the lateral resistance of the pile cap are discussed and compared in the paper. One is from the design standard of Federal Emergency Management Agency, Prestandard and Commentary for the Seismic Rehabilitation of Buildings, FEMA 356 (2000), another is from Chinese design code, Technical Code for Building Pile Foundations, JGJ 94-94 (1995). When the lateral resistance of the pile cap is considered, an optimum spacing is found for a large strip-shape pile group to provide maximum lateral resistance. A case study is presented by using this design approach.

DESIGN METHODOLOGY

Mokwa (1999) performed thirty-one load tests on three groups of piles with embedded caps, on two single piles, and on a buried concrete bulkhead. Based on the load test results, an approach called as pile cap p-y curve was presented to estimate the passive earth pressures developed in front of the pile cap. The relationship between the passive soil pressure and the pile cap deflection is represented by p-y curves using a hyperbolic formulation. This approach is included in FEMA 356 as shown in Fig. 1. Passive pressure mobilization of the pile cap shall be calculated on the basis of the ultimate passive pressure and the ratio of the lateral displacement over the pile thickness.

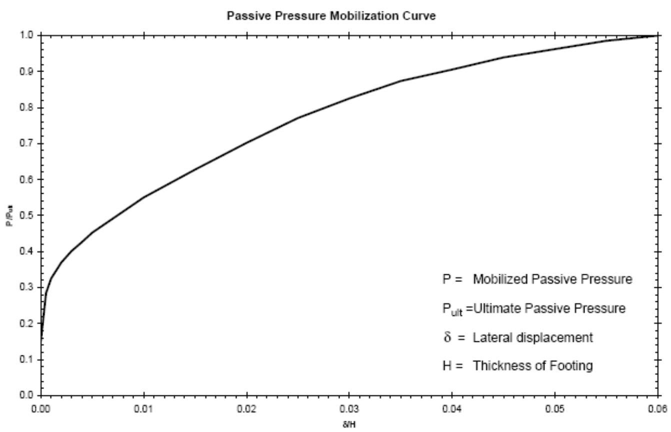

Fig 1. Passive Pressure Mobilization Curve (FEMA, 2000)

Based on Chinese design code JGJ 94-94, the lateral resistance of the pile cap can include two components: the lateral earth resistance in the front of the pile cap and the friction resistance between the bottom of the pile cap and the soil. The last component is generally ignored in practice, because the contact between the bottom of the pile cap and the soil is not always guaranteed. The second component is related to the thickness, width, and side soil resistance of the pile cap. The lateral deflection of pile and pile cap is limited to 6 mm or 10 mm on the basis of the importance of the infrastructure. The soil resistance to the pile cap is assumed as elastic for small deflection and is simulated as Winkler springs. The stiffness of the spring is assumed as increased with depth by a factor *m* shown in Fig. 2. The value of *m* can be developed from the static lateral load test or using the default value in JGJ 94-94.

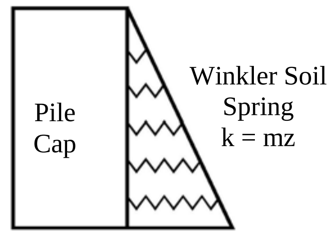

Fig. 2. Lateral Resistance of Pile Cap based on JGJ 94-94

PILE GROUP ANALYSIS

Piles installed in groups at close spacing takes less load than a single pile subjected to the same lateral deflection because of the group effect. The group effect is caused by the overlap of the resistance zones of piles and the consequential reduction of lateral soil resistance. Many researchers (e.g. Prakash and Saran 1967, Brown and Reese 1985, McVay et al. 1998) have performed the pile group load tests and presented different approaches to consider the group effect. The widely used approach in current practices is to use the concept of p-multipliers described by Brown et al. (1988). This approach for analyzing the behavior of pile in a group is similar to the approach used for analysis of a single pile, except that the p-value are reduced using a p-multiplier to account for the group effect. The value of the p-multiplier is related to the pile spacing and the pile location within the group. Leading row in a pile group has a higher value of p-multiplier than that of trailing row because the overlap of the resistance zone for trailing row is more significant. The average value of p-multipliers of all piles is used to represent the group efficiency of pile group in the design practice. Mokwa and Ducan (2001) provided a design chart for estimating the value of p-multipliers as functions of pile group arrangement and pile spacing. The design chart shown in Fig. 3 summarized the results from previous experimental studies including full-scale field lateral load tests and centrifuge tests. The tabular value of the design chart is presented in Table 1. The group effect is not significant when the pile spacing parallel to the load exceeds six pile diameters center-to-center.

The group effect is considered in a similar way in the Chinese design code by the group efficiency. A uniform equation is presented to calculate the pile group efficiency on the basis of the statistical analysis of the 48 lateral pile group load test results performed national wide. Different with the United State's practice, the group efficiency is not only related to pile spacing and rows of piles in load direction, but also rows of piles perpendicular to load direction.

Usually, either seismic or wind load is significant when lateral load controls the structure design. These loads can be applied in any direction of a pile group. Therefore, both directions of the pile group should be checked if enough lateral capacity can be applied to resist the load. When the pile cap can be considered for resisting the lateral load, the longer side of the strip-shape pile cap can provide much more lateral resistance than shorter side and will not control the design. As indicated in Table 1, a larger spacing would provide a higher group efficiency for a pile group. It is possible that a pile group with a larger spacing and less piles would provide similar or more lateral capacity due to higher group efficiency. In other ward, an optimum spacing could exist in the shorter side of a large strip-shape pile group to provide maximum lateral resistance.

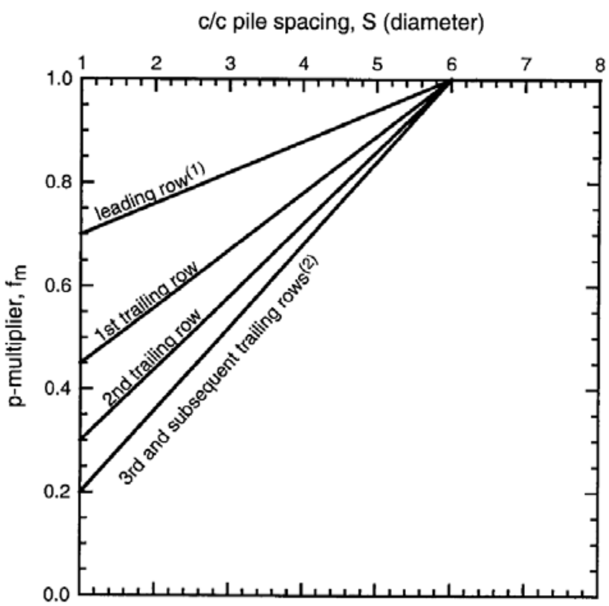

Fig. 3. P-multiplier design curve (Mokwa and Ducan 2001)

Table 1. Recommended Value of the P-multiplier

Pile Position	Pile Spacing as Pile Diameter					
	1	2	3	4	5	6
Leading Row	0.70	0.75	0.82	0.87	0.94	1.00
Second Row	0.45	0.56	0.67	0.78	0.88	1.00
Third Row	0.30	0.43	0.57	0.72	0.86	1.00
Fourth Row	0.20	0.36	0.52	0.67	0.84	1.00

CASE STUDY

A natural gas turbine power plant is being built on the south bank of the Yangtze River, near Nanjing City, China. The project site is located on existing farmland that includes fishing ponds. Subsurface investigations indicated that significant deep soft clay deposits exist in the plant area. To address this situation, prestressed high strength concrete (PHC) piles are being used to support important structures, such as the turbine pedestal.

The soil profile at the main building area was summarized from the site investigation, which included standard penetration tests (SPT) and cone penetration test (CPT) soundings. Soil properties were developed from laboratory testing shown in Fig. 4. To guarantee that the pile tips would be driven into the dense sand layer, the project owner required the use of a 32 m long PHC pile. Based on the soil properties, the axial capacities were estimated as 1550 kilonewtons (kN) for compression and 775 kN for tension. The lateral capacity was developed using the LPILE program and verified by the load tests. The parameters for the LPILE analysis were estimated using data from the LPILE user's manual and previous studies (Prakash and Kumar 1996). In the LPILE program, the PHC pile was simulated as a hollow circular prestressed concrete pile. Both free head and fixed head conditions were considered. The results indicated that a single pile had an allowable lateral capacity of 122 kN and 207 kN for the free and fixed head conditions, respectively. The allowable lateral capacity was defined as the capacity at 10 millimeters (mm) deflection (JGJ 94-94 1995).

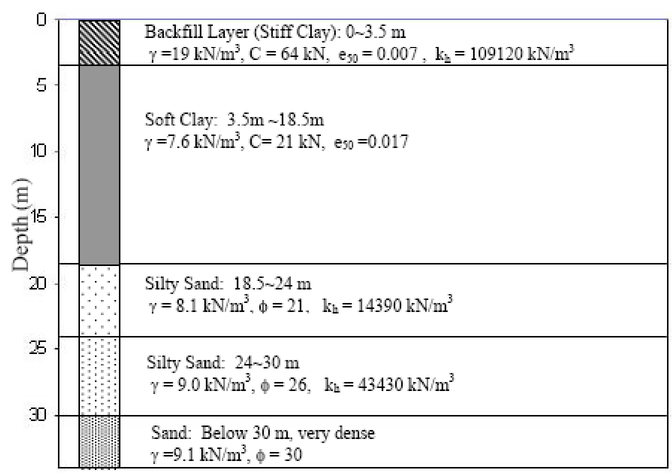

Fig. 4. Soil profile at project site

The turbine pedestal for the project is a 12.5 m by 56.5 m mat foundation, which is used to support the gas and steam turbines during power plant operation. The thickness of the mat varies from 2 m to 5 m. Structural analysis indicated that lateral load, as a result of seismic design, would control the pile group design. If the lateral resistance of the pile cap could not be considered, the pile group can not be layout because the minimum pile spacing should not be less than 3.5 diameters for this kind of pile (JGJ 94-94 1995). As indicated in Fig. 4, the first soil layer is backfill with compacted stiff clay. This layer was compacted to 95% of the maximum dry density. There should have a good contact between the soil and the pile cap. The cap resistance with 2 m thickness was considered for the lateral load.

The initial pile layout used 3.5 diameters for both directions of the pile group and 140 piles would be required to resist the lateral load. With the cooperation of structural engineers, the pile group layout was determined for the different spacings in the shorter side of the pile group, but keeping 3.5 diameter spacing in the longer side. The group efficiency and the pile cap resistance were calculated using the Chinese design code, but were checked with the United State's practices. The load factors for the infrastructure importance and seismic design were also considered. The relationship of the pile group lateral capacity versus the pile spacing is shown on Fig. 5. The pile cap resistance is converted to equivalent group efficiency added to the total group efficiency. The total number of piling from certain spacing and the total group efficiency are indicated as values in parentheses shown in Fig. 5. The maximum spacing for the compression is also indicated on the figure; for this case, the optimum pile spacing is approximately 3.8 pile diameters. The four pile diameter spacing was selected for the final design, and the number of piles was reduced to 114, which is a 15 percent reduction from the original design.

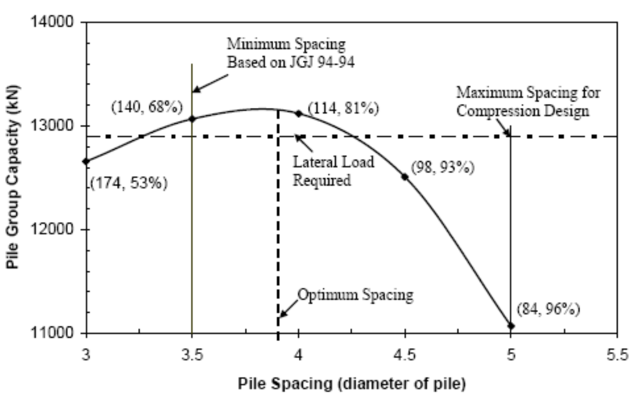

Fig. 5. Pile group lateral capacity versus pile spacing

CONCLUSION

The lateral soil resistance to the pile cap is generally neglected for a pile group design in United States practice. One concern is that the cap deflection may not be enough to fully mobilize the passive resistance. Two methodologies based on both American and Chinese codes are presented in the paper to rationally calculate this lateral resistance when the cap deflection is small. Another concern is that the possibility that soil can settle away from the cap and the contact between the pile cap and the soil may not be guaranteed. Whether the lateral soil resistance to the pile cap can be included into the design is dependent on the soil type and the construction method. The soil resistance of the pile cap can be significant when the pile cap is large and thick.

When the pile cap can be considered to provide resistance to the lateral later, an optimum spacing is found for a large strip-shape pile group to provide maximum lateral resistance. For a large strip-shape pile group, the case with lateral load direction perpendicular to longer side of pile cap does not control the design because the cap resistance is much more than that of the case with lateral load direction perpendicular to shorter side of pile cap. The group efficiency of a pile group is increased with increase of the pile spacing. Therefore, it is possible to use larger pile spacing with less pile to provide similar or larger lateral capacity through adjusting the pile spacing along the shorter side of the strip-shape pile group. Cooperation was required between geotechnical engineers and structural engineers to optimize the spacing. For the case study, the optimized spacing saved 15 percent of the piling compared to the initial design.

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